



## NASA SBIR 2022 Phase I Solicitation

### H3.08 Challenges in Carbon Dioxide Removal and Reduction: Carbon Particulate and Thermal Management

Lead Center: MSFC

Participating Center(s): ARC, GRC, JPL, JSC, KSC

#### Scope Title:

Advancements in Carbon Dioxide Reduction

#### Scope Description:

Air Revitalization Systems (ARS) are necessary for human survival during space exploration missions. Technologies to efficiently remove carbon dioxide (CO<sub>2</sub>) from the cabin atmosphere and to reduce the captured CO<sub>2</sub> to recover oxygen are two systems that face technical challenges. Using adsorption beds to remove CO<sub>2</sub> is a proven technology, but optimization is needed. Please see the second scope "Advanced Heaters for Solid Sorption Systems" for more information. In the area of CO<sub>2</sub> reduction, several technologies produce solid carbon either intentionally or unintentionally. A current challenge to the development of these technologies is carbon management. Technologies and methods that will efficiently separate, remove, and store the carbon are sought. Technical solutions will allow for efficient operation of the carbon reduction process, prevent contamination of downstream hardware receiving effluent gases and avoid contamination of cabin atmosphere during carbon handling and disposal.

Oxygen recovery technology options, including carbon formation reactors and methane pyrolysis reactors, almost universally result in particulates in the form of solid carbon or solid hydrocarbons. Mitigation for these particulates will be essential to the success and maintainability of these systems during long-duration missions. Techniques and methods leading to compact, regenerable devices or components for removing, managing, and disposing of residual particulate matter within Environmental Control and Life Support Systems (ECLSS) process equipment are sought.

NASA has invested in many CO<sub>2</sub> reduction technologies over the years to increase the percentage of oxygen recovery from CO<sub>2</sub> in human spacecraft for long-duration missions. Examples of technologies include, but are not limited to, Series-Bosch, Continuous Bosch, methane pyrolysis, and microfluidic carbon dioxide electrolysis. Significant technical challenges still face these process technologies and are impeding progress in technology maturation. Critical technical elements of these technologies have a high degree of technical difficulty.

Examples where additional component technology development is needed include (this is a partial list):

- Separation of particulate carbon from process gas streams.
- Safe collection, removal, and disposal of solid carbon, including cases when continuously operating

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reactors are active.

- Subsystems to recharge reactors with new catalyst and to efficiently reuse or recycle consumable catalysts.
- Technology solutions to mitigate solid carbon clogging of frits and filters in recycle gas streams.

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Separation performance approaching HEPA rating is desired for ultrafine particulate matter with minimal pressure drop. The separator function should be capable of operating for hours at high particle loading rates. If necessary, periodic operations and methods could be employed to restore capacity/functionality back to nearly 100% of its original clean state through in-place and autonomous regeneration or self-cleaning operations using minimal or no consumables (including media-free hydrodynamic separators). The device must minimize crew exposure to accumulated particulate matter and enable easy particulate matter disposal or chemical repurposing.

This subtopic is open to consider novel ideas that address any of the numerous technical challenges that face development of CO<sub>2</sub> reduction hardware with particular attention to solid carbon management.

**Expected TRL or TRL Range at completion of the Project:**

2 to 5

**Primary Technology Taxonomy:**

Level 1: TX 06 Human Health, Life Support, and Habitation Systems

Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Hardware
- Prototype

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**Desired Deliverables Description:**

Phase I deliverables: Reports demonstrating proof of concept and test data from proof-of-concept studies, concepts, and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Conceptual solution in Phase I should look ahead to satisfying the requirement of limiting crew exposure to the raw carbon dust as well as carbon exposure to downstream hardware.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Prototypes must be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. The system should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

**State of the Art and Critical Gaps:**

Advanced oxygen recovery systems are necessary for long-duration missions as resupply of consumables will not be available.Â The state-of-the-art Sabatier system, which has flown on the International Space Station (ISS) as the Carbon Dioxide Reduction Assembly (CRA), only recovers about half of the oxygen from metabolic CO<sub>2</sub>. This is because there is insufficient hydrogen to react all available CO<sub>2</sub>. The Sabatier reacts hydrogen with CO<sub>2</sub> to produce methane and water.Â The methane is vented overboard as a waste product causing a net loss of hydrogen. Mars

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missions target >75% oxygen recovery from CO<sub>2</sub>, with a goal to approach 100% recovery. NASA is developing several alternate technologies that have the potential to increase the percentage of oxygen recovery from CO<sub>2</sub>, toward fully closing the ARS loop. Methane pyrolysis recovers hydrogen from methane, making additional hydrogen available to react with CO<sub>2</sub>. Other technologies under investigation process CO<sub>2</sub>, recovering a higher percentage of oxygen than the Sabatier. All these alternative systems, however, need additional technology investment to reach a level of maturity necessary for consideration for use in a flight ECLSS.

Several of these alternative systems produce solid carbon either intentionally or unintentionally and solutions for safely filtering, removing, and storing solid carbon are critical to the maturation of these systems.

#### **Relevance / Science Traceability:**

These technologies would be essential and enabling to long-duration human exploration missions, in cases where closure of the atmosphere revitalization loop will trade over alternate ECLSS architectures. The atmosphere revitalization loop on the ISS is only about 50% closed when the Sabatier is operational. These technologies may be applicable to Gateway, lunar surface, and Mars, including surface and transit missions. This technology could be proven on the ISS as a flight demonstration.

This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in the area of atmosphere revitalization, and specifically, in the areas of CO<sub>2</sub> reduction and oxygen recovery, functional areas of ECLSS.

The Life Support Systems (LSS) Project, under the Advanced Exploration Systems (AES) Program, within the Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer. The LSS Project would be in position to sponsor Phase III and technology infusion.

#### **References:**

1. "Hydrogen Recovery by Methane Pyrolysis to Elemental Carbon" (49th International Conference on Environmental Systems, ICES-2019-103)
2. "Evolving Maturation of the Series-Bosch System" (47th International Conference on Environmental Systems, ICES-2017-219)
3. "State of NASA Oxygen Recovery" (48th International Conference on Environmental Systems, ICES-2018-48)
4. "Particulate Filtration from Emissions of a Plasma Pyrolysis Assembly Reactor Using Regenerable Porous Metal Filters" (47th International Conference on Environmental Systems, ICES-2017-174)
5. "Methane Post-Processing and Hydrogen Separation for Spacecraft Oxygen Loop Closure" (47th International Conference on Environmental Systems, ICES-2017-182)
6. "Trading Advanced Oxygen Recovery Architectures and Technologies" (48th International Conference on Environmental Systems, ICES-2018-321)
7. NASA-STD-3001, VOLUME 2, REVISION A, Section 6.4.4.1 "For missions longer than 14 days, the system shall limit the concentration in the cabin atmosphere of particulate matter ranging from 0.5 µm to 10 µm (respirable fraction) in aerodynamic diameter to <1 mg/m<sup>3</sup> and 10 µm to 100 µm to <3 mg/m<sup>3</sup>." <https://www.nasa.gov/sites/default/files/atoms/files/nasa-std-3001-vol-2a.pdf>

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#### **Scope Title:**

Advanced Heaters for Sorbent Systems

#### **Scope Description:**

Spacecraft carbon dioxide (CO<sub>2</sub>), water, and trace contaminant (organics) removal systems must be regenerable and reliable and minimize resupply and equivalent system mass (ESM). In most sorbent systems, heat is used to regenerate the beds by expelling contaminants for disposal or to downstream processes for resource recovery.Â In future deep space exploration missions, such as those to the Moon and to Mars, sorption systems must drastically reduce power to minimize the dependence on scarce resources. The state-of-the-art (SOA) spacecraft sorption

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systems utilize commercial off-the-shelf (COTS) resistive heaters coupled with conductive fins. These Joule heating methods lead to inefficiencies such as high thermal contact resistance, high temperature differential within the sorption beds, high component mass and volumes, and long ramp-up times. The SOA cooling options utilize blowers, cooling channels or cold plates in conjunction with spacecraft liquid cooling loops. Since the spacecraft cooling systems are limited in capacity, efficient cooling methods are needed. Although it is recognized that the conductivity of the sorbent material is the limiting factor to the heating of sorption beds, it is also important to design integrated thermal management systems that transfer the heat quickly, uniformly, and efficiently throughout the bed. Some suggested, but not inclusive, areas of heater improvements are listed here:

- Decreasing the contact resistance between the heaters and the sorbent media.
- Increasing temperature uniformity within the sorbent beds.
- Improving tolerance to corrosion.
- Optimizing for various configurations of sorbent media, including granules, beads, porous solids, additively manufactured, and liquid sorbents.

Some thermal management components can function both as heaters and coolers. This will lead to reduced system mass and volume of heaters, fin stock, cooling channels, various supporting hardware, and sorption materials. Proposed concepts may include different heater types as well as heater configurations. Heater configurations could include those that are bound or embedded into the sorbent media.

This subtopic solicits advanced thermal management systems that offer a significant improvement over the SOA. The heaters, coolers, configurations, and all attached hardware must meet the following operational requirements:

- Continuous operation at temperatures as high as 200 °C or above.
- Minimize both heating and cooling rates compared to the SOA heaters capability.
- Heaters and cooling options must be able to operate in temperature swing sorption systems continuously 24 hours a day. Some example cycle times are those used in the current spacecraft system: the Carbon Dioxide Removal Assembly used a 144-minute cycle time; The 4BCO<sub>2</sub> beds operate on 80-minute cycle times.
- Compatible with either liquid or solid sorbent systems.
- Capable of operating in microgravity and reduced gravity environment.
- Must be compatible with sorbent regeneration or thermally sorbent systems.
- Must be able to operate continuously for 3 years.
- Offer an improvement in heat conservation, efficiency, power consumption, reliability, resupply, and ESM over the spacecraft SOA systems.
- Heaters and cooling options must utilize the available power and cooling options expected in exploration spacecraft such as avionics air, the low-temperature loops, and the medium-temperature loops.
- Meet the space station safety requirement.

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#### **Expected TRL or TRL Range at completion of the Project:**

2 to 4

#### **Primary Technology Taxonomy:**

Level 1: TX 06 Human Health, Life Support, and Habitation Systems

Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

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#### **Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype

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- Hardware

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### **Desired Deliverables Description:**

Phase I deliverables: Reports demonstrating proof of concept and test data from proof-of-concept studies, concepts, and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Phase I analysis should include a trade study between the advanced heaters and the SOA and operation in the spacecraft environments.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data, and analysis. Prototypes must be for sorption beds sized for 4 crew members. Robustness must be demonstrated with extended operation and with periods of intermittent dormancy. Systems should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

### **State of the Art and Critical Gaps:**

Current and future human exploration missions require regenerable systems that minimize mass, power, volume, and resupply and are highly reliable.Â Most SOA sorption systems in the Atmosphere Revitalization System (ARS) use COTS heaters that are inefficient, leading to high power requirements.Â Thermal management in systems such as the Carbon Dioxide Removal Assembly and the Sabatier could be improved by using advanced heating systems.Â Unfortunately, innovative heaters such as heat pipes and vapor chambers have been used elsewhere in space hardware but have yet to be developed for use in Environmental Control and Life Support Systems (ECLSS).

In addition, a significant amount of the spacecraft power is allocated to a variety of ECLSS. Alternative thermal management approaches that have multiple functions such as heating, cooling, thermal energy storage, and the thermal energy transfer over long distances will drastically reduce the loading on available resources for both in-transit and planetary base missions. These advanced heaters can be used for other NASA mission architectures as well, such as the extravehicular activity (EVA) and the Trash Compaction Processing System.

### **Relevance / Science Traceability:**

This subtopic is relevant to Human Exploration and Operations Mission Directorate (HEOMD), especially ECLSS, by improving thermal management systems to minimize loading on facility resources such as power, heater, and cooling systems. In addition, efficient heaters minimize mass, power, and volume. The following ECLSS systems could benefit from improvements in thermal management technology: the ARSs, the Water Management Systems, and Solid Waste Management Systems including trash compaction. Other technical areas that may have interest are small satellites and EVA.

### **References:**

1. Cmarik, Gregory, James Knox, and Warren Peters. "4-Bed CO2 Scrubberâ&#128;#147;From Design to Build." 2020 International Conference on Environmental Systems, 2020.
2. Peterson, G. P., and H. B. Ma. "Theoretical analysis of the maximum heat transport in triangular grooves: a study of idealized micro heat pipes." (1996): 731-739.
3. Â Schunk, Richard, Warren Peters, and John Thomas. "Four Bed Molecular Sieveâ&#128;#147;Exploration (4BMS-X) Virtual Heater Design and Optimization." 47th International Conference on Environmental Systems, 2017.
4. Wang, G., D. Mishkinis, and D. Nikanpour, "Capillary heat loop technology: space applications and recent Canadian activities." Applied thermal engineering, 2008. 28(4): p. 284-303.
5. Tra-My Justine Richardson and Darrell Jan. "A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierarchy Process", 48th International Conference on Environmental Systems, ICES-2018-332

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